# Simulation Pipeline of Milliscale Magnetic Robots for Blood Clot Removal


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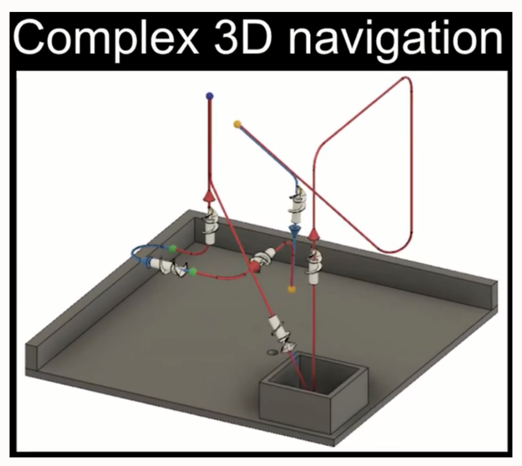
## Background

- Blood clot removal improves patient's outcome if performed promptly. However current treatments options for blood clots, such as thrombolytic medications and catheter systems, may produce complications such as infections, damage to the blood vessels, or life threatening bleeding.
- Milliscale, magnetically controlled robots (swimmers) can be used to tetherlessly dislodge blood clots with high precision and control, which may be less invasive and less dangerous than alternatives to blood clot removal.



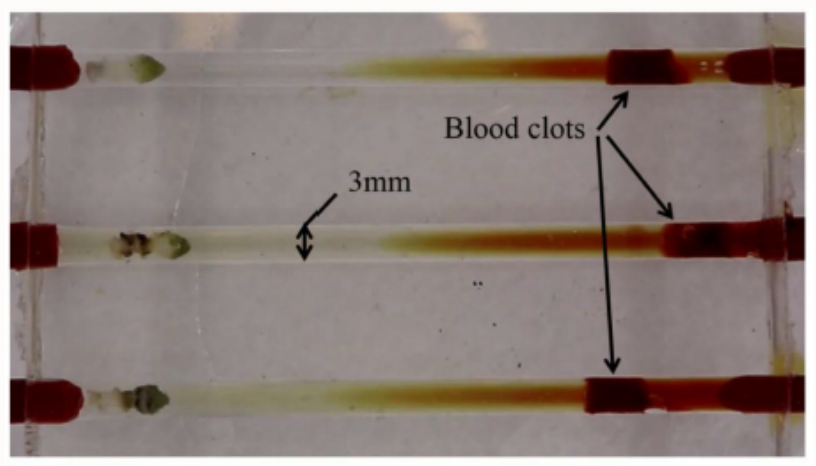
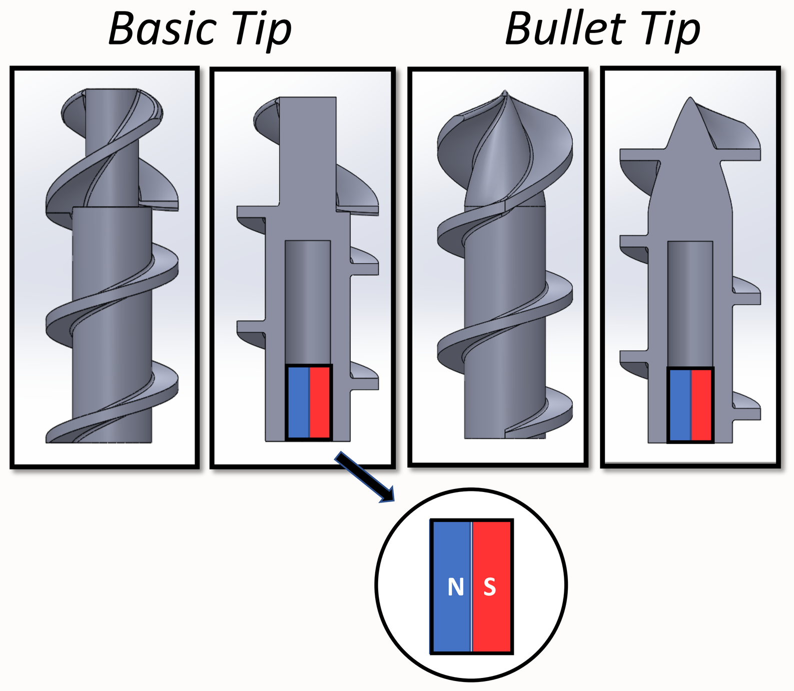




Figure taken from [1]

## Objective

- Optimize the robot's shape for swimming efficiency.
- Evaluate the established pipeline for simulated design testing with data visualization.
- Compute the rotational frequency required to maintain a neutral hovering position of each simulated design test.

## Design




Swimmers have an internal hole for holding the diametrically magnetized permanent magnet and air pocket.

Variations in pitch, thread depth, and air pocket size were tested between the bullet and basic tip designs.

## References and Acknowledgments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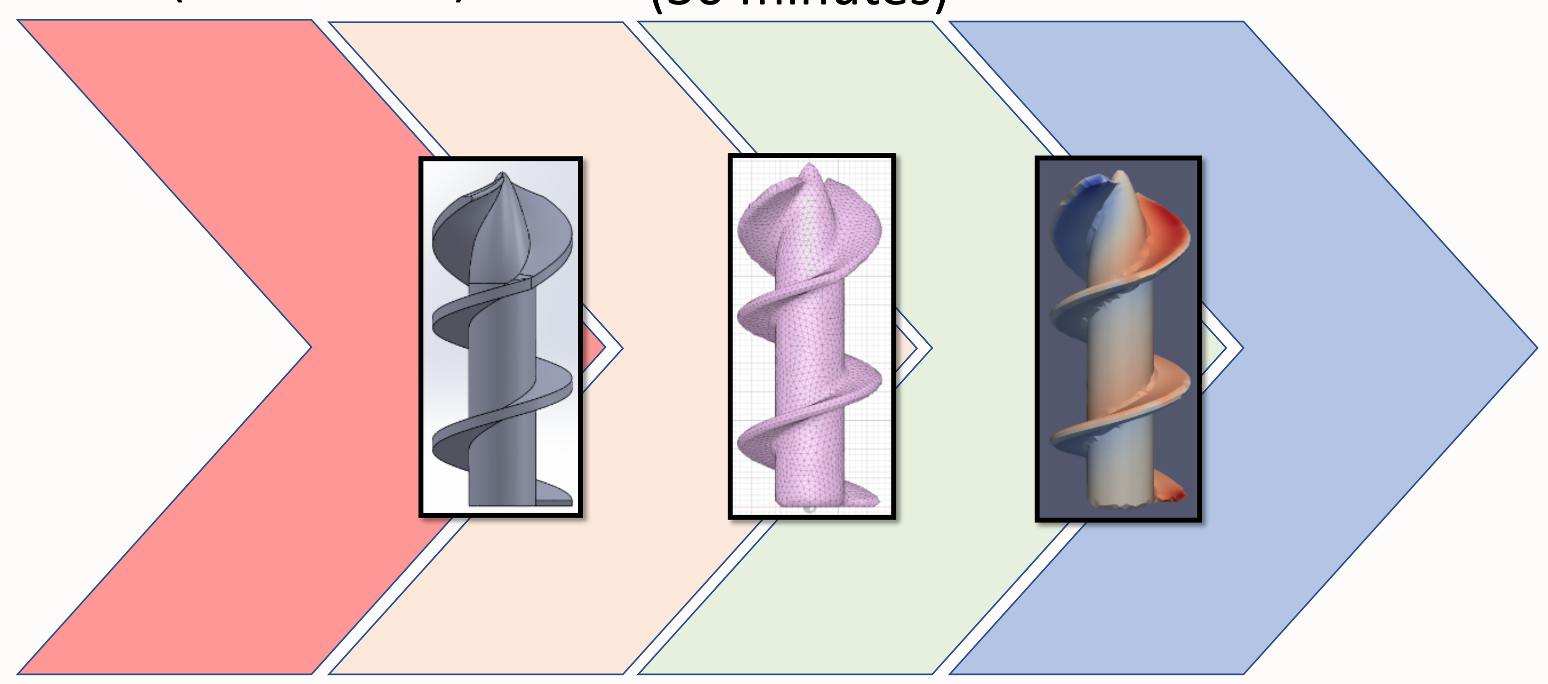
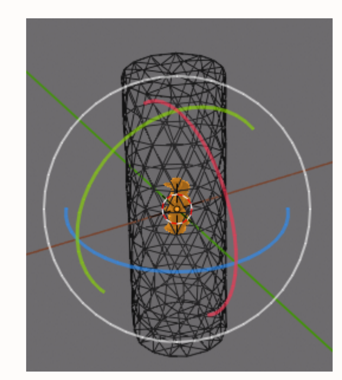
Leclerc, J., Zhao, H., Bao, D., & T. Becker, A. (2020). In Vitro Design Investigation of a Rotating Helical Magnetic Swimmer for Combined 3-D Navigation and Blood Clot Removal. IEEE Transactions on Robotics, 1–8. https://doi.org/10.1109/TRO.2020.2988636[1]

Heinrich, J.C. and Vionnet C.A. (1995). The penalty method for the Navier-Stokes equations. *Archives of Computational Methods in Engineering,2(2), 51-65.* [2]


## Simulation

### Mesh editing



- Design meshes are nested inside of a meshed boundary that represents the arterial walls. Simulations of blood flow are run in the volume between the two geometries.

### Navier-Stokes Equations

- Incompressible flow of a viscous fluid around the geometry is approximated using the Navier-Stokes equations.
- The velocity vector field and pressure gradient around the swimmer are approximated when assuming selected rotation frequencies and translational velocity. [1]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0.$$

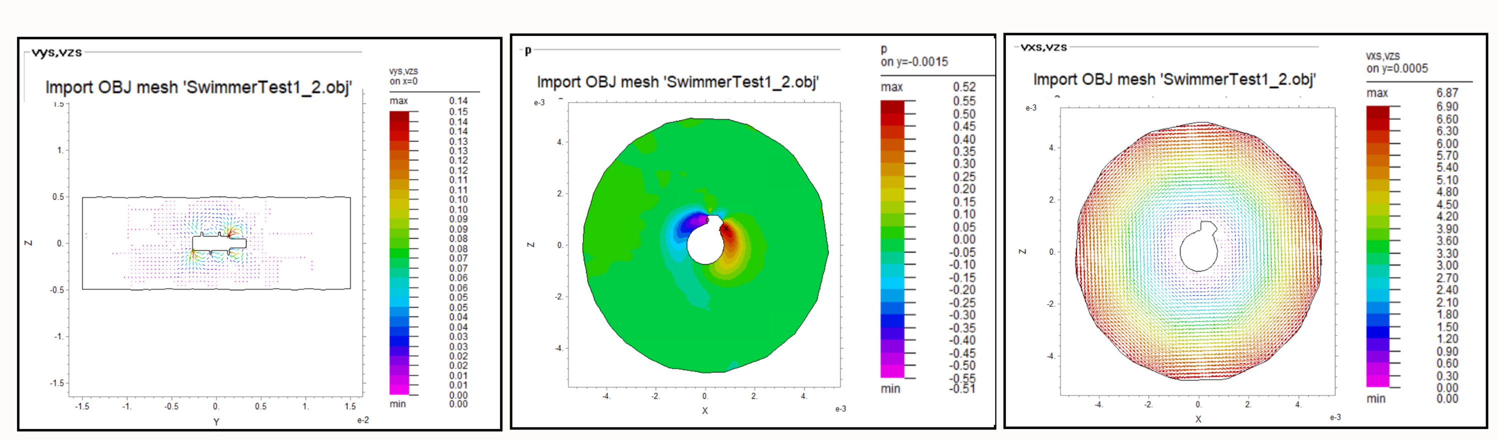
$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z.$$

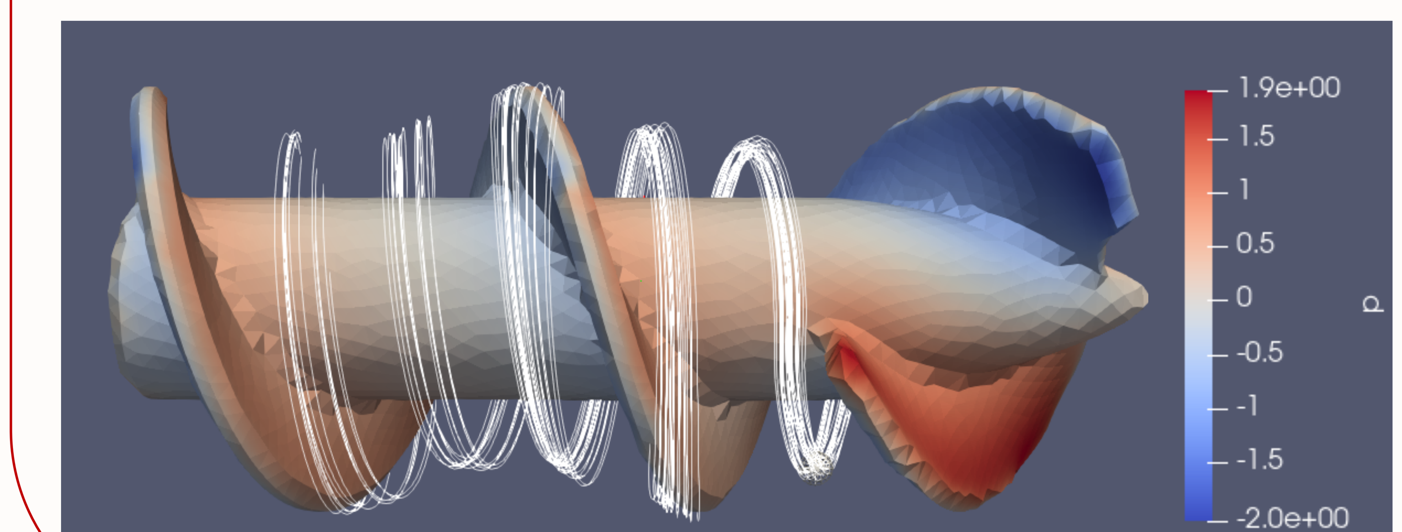
### Penalty Method [2]

- This method is introduced to approximate the requirement of the Navier Stokes equations that Div(V)=0.
- Use of a higher penalty factor yields a result that more closely approximates this requirement.




## Post-processing

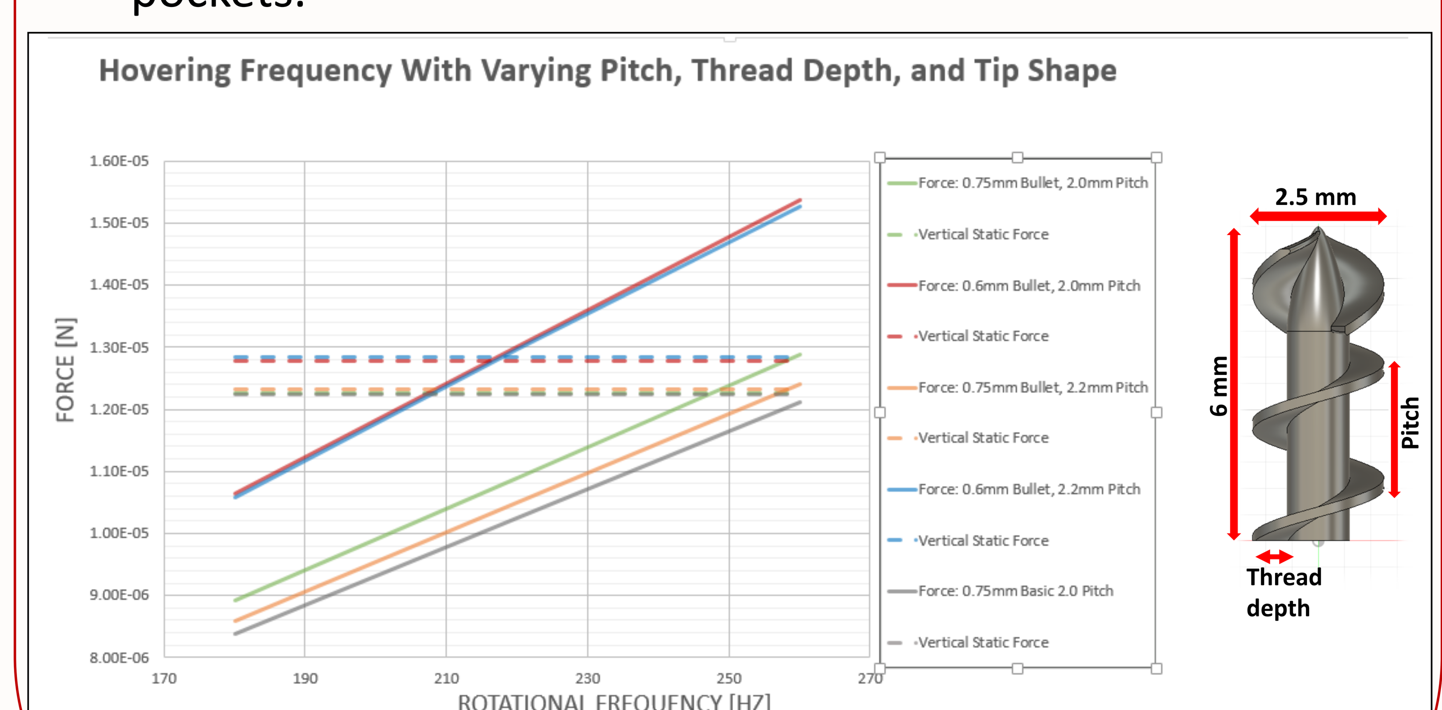
- Visualization of pressure is shown as the color on the swimmer surface.
- Higher accuracy is signified by low amounts of overlapping of the flow lines with the swimmer geometry.
- Propulsive force is found at different rotation frequencies of the swimmers.




## Results

### Hovering frequency

- Vertical static force is equal to the difference between weight and the buoyant force generated from the air pocket.
- The hovering frequency is found where the force of weight and buoyancy is equal to the force generated from the swimmer's rotation.
- The most efficient swimmers hovered at around 216Hz with the bullet tip, 2mm pitch, deeper threads, and larger air pockets.




## Conclusion and Future Work

- Verify the model with experimental tests.
- Automating the design process to alter design geometry, edit text files, run simulations, and apply filters for final calculations.
- Including inertial force into future calculations with FlexPDE.